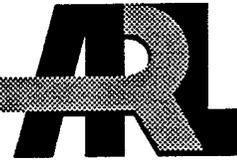


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Impact Effects in Multilayered Plates

by Jonas A. Zukas
and Daniel R. Scheffler

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Impact Effects in Multilayered Plates

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Abstract

This report presents results of numerical simulations of impact effects in monoblock and multilayered plates using both Lagrangian and Eulerian wave propagation codes. It is found that Lagrangian simulations compare favorably with experimental and analytical results. Eulerian codes, while ideal for large distortion situations such as penetration, have great difficulty in describing multiplate perforation due primarily to problems with the interface treatment in Eulerian codes.

This report was originally presented as a paper at the Special Symposium Honoring the 70th Birthdays of Professors Jack Vinson and Charlie Bert, which was part of the 1999 ASME International Mechanical Engineering Congress and Exposition held in Nashville, TN, on 14–19 November 1999. The paper has been accepted for publication in a special volume of *The Journal on Solid and Structures*.

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1. Introduction

Impact and impulsive loading onto layered media (targets consisting of different materials) is a long standing problem. It occurs naturally when dealing with impact effects in geological media where different strata have different material properties. It can occur in the design of protective structures where materials of different density, strength, and cross-sectional area are employed to reduce the intensity of the impact stress. Many examples can be found in the works of Rinehart [1] and Tedesco and Landis [2]. This aspect of the impact problem is well understood and covered in modern textbooks and reference books dealing with transient phenomena.

One aspect of layering involves the impact of projectiles onto targets consisting of multiple layers of plates of the same density. In impact testing, this often occurs when very thick targets need to be constructed, yet the material is not manufactured in the required thickness. One example is the requirement to construct a "semi-infinite" target, one where the rear of the plate does not influence the penetration process. The total thickness can be made up by stacking identical layers of smaller thicknesses to reach the desired target thickness. This target stack is then contained in some fashion (e.g., strapped or welded at the periphery). The situation also arises in laboratory tests when measuring wave arrival times or pressures in situ. The method by which probes are inserted in the target can dramatically change wave propagation behavior. Netherwood [3], conducting in situ pressure measurements of impacted plates, found that multilayer targets are much weaker than solid ones of the same thickness; therefore, the mechanism of penetration was distinctly different for the two types of targets. Nixdorff [4] analytically examined the effect of lamination on the ballistic limit for up to five layers, and found considerable differences as the number of layers increased. Segletes and Zukas [5] and Zukas [6], in numerical studies of layered targets with Lagrangian codes, obtained similar results.

Multilayer targets can be grouped into three classes:

- (a) thin targets ($T/D < 1$, where T = target thickness and D = projectile diameter)
- (b) intermediate thickness targets ($3 < T/D < 10$)

(c) thick targets ($T/D > 10$)

Zaid, El-Kalai, and Travis [7], Eleiche, Abdel-Kader, and Almohandes [8], and Gupta and Madhu [9] (as well as the previously cited references) found that for thin targets, the multilayer plate is much weaker than the solid one of the same thickness. Other studies could be cited, but these studies suffice to show that for thin targets, lamination can alter the response mechanism under impact loading and fail to correlate with the behavior of a solid target, especially if the number of layers is large.

For thick targets, correlation between impact effects in a solid target and one made of layers of identical material can be quite good, especially for T/D ratios that are very large. Care must be taken to insure that the target is sufficiently large in the radial direction so that boundary effects do not influence penetration phenomena [10].

The response of intermediate thickness targets can exhibit characteristics of both thin and thick target response, depending on T/D , material properties, striker geometry, and initial conditions.

2. Intermediate Thickness Targets

2.1 Lagrangian Calculations. The problem for intermediate thickness targets can be seen from the following calculations. The ZeuS code [5,11,12], a two-dimensional, Lagrangian explicit finite element code for fast, transient analysis on personal computers, was used to calculate the impact of a 64.5-g S-7 tool steel projectile with length-to-diameter (L/D) ratio of five into a single rolled homogeneous armor (RHA) plate with a thickness of 3.18 cm. The projectile had a diameter of 1.3 cm and a striking velocity of 1,164 m/s. Experimental data were taken from the report by Lambert [13]. The experimentally determined values of residual mass and residual velocity were 22.9 grams and 223 m/s, respectively. ZeuS calculations indicated a residual mass of 25.5 g and a residual velocity of 233 m/s. These results were deemed acceptably close. Material properties for the calculations were taken from split-Hopkinson bar results published by Nicholas [14].

Next, a series of calculations was performed where the solid target was assumed to consist of two, four, and six layers, each with properties identical to those of the solid target. Figure 1 shows penetration of the four-layer target at various times. The variation of projectile normalized residual mass (m_r/m_0) and normalized residual velocity (V_r/V_s , where V_s is the striking velocity) can be seen in Figures 2 and 3. With the four-layer target, the difference between Lambert's data for the solid target and the computed residual masses is 43%, while for the residual velocity it is 143%. The differences continue to increase with additional layering.

Even though the plates in the multilayer target have the same density and material properties as the solid target, the differences noted could be anticipated. The plates in the multilayer target are not restrained; hence, they can slip freely over each other. As they separate, a free surface is created. The inability of a free surface to support rarefaction waves changes the stress wave propagation characteristics of multiplate penetration events at early times. As these stress variations are integrated in time, the difference between the simulations becomes more visible, with the multiplate case demonstrating more bending than the equivalent solid plate case (Fig. 4). This can also be inferred from plate theory, which gives for the bending stiffness of the plate $D = ET^3/12(1-\nu^2)$, where E is the elastic modulus, T the plate thickness, and ν Poisson's ratio. Since bending stiffness follows plate thickness to the third power, simply cutting a monoblock plate in half reduces its bending stiffness by a factor of eight.

There is no direct experimental evidence for the behavior of the layered plate. However, we can establish confidence in the validity of the Lagrangian calculations from the following considerations. First, the calculation for the residual mass and velocity of the monolithic plate agree closely with the experimental data of Lambert, cited previously. Second, Eleiche, Abdel-Kader, and Almohandes [8] present experimental data for impacts into steel and fiberglass-reinforced polyester (FRP) plates consisting of one to eight layers. Some target arrays consist of plates in direct contact, while others include air gaps ranging from one to three plate thicknesses. Their experiments were conducted with thinner plates (8 mm) than considered here, yet show the same trends; the normalized residual velocity ranged from 0.62 for a single plate perforation to 0.73 for perforation of a stack of eight plates, with a total thickness equivalent to that of the single plate. Finally,

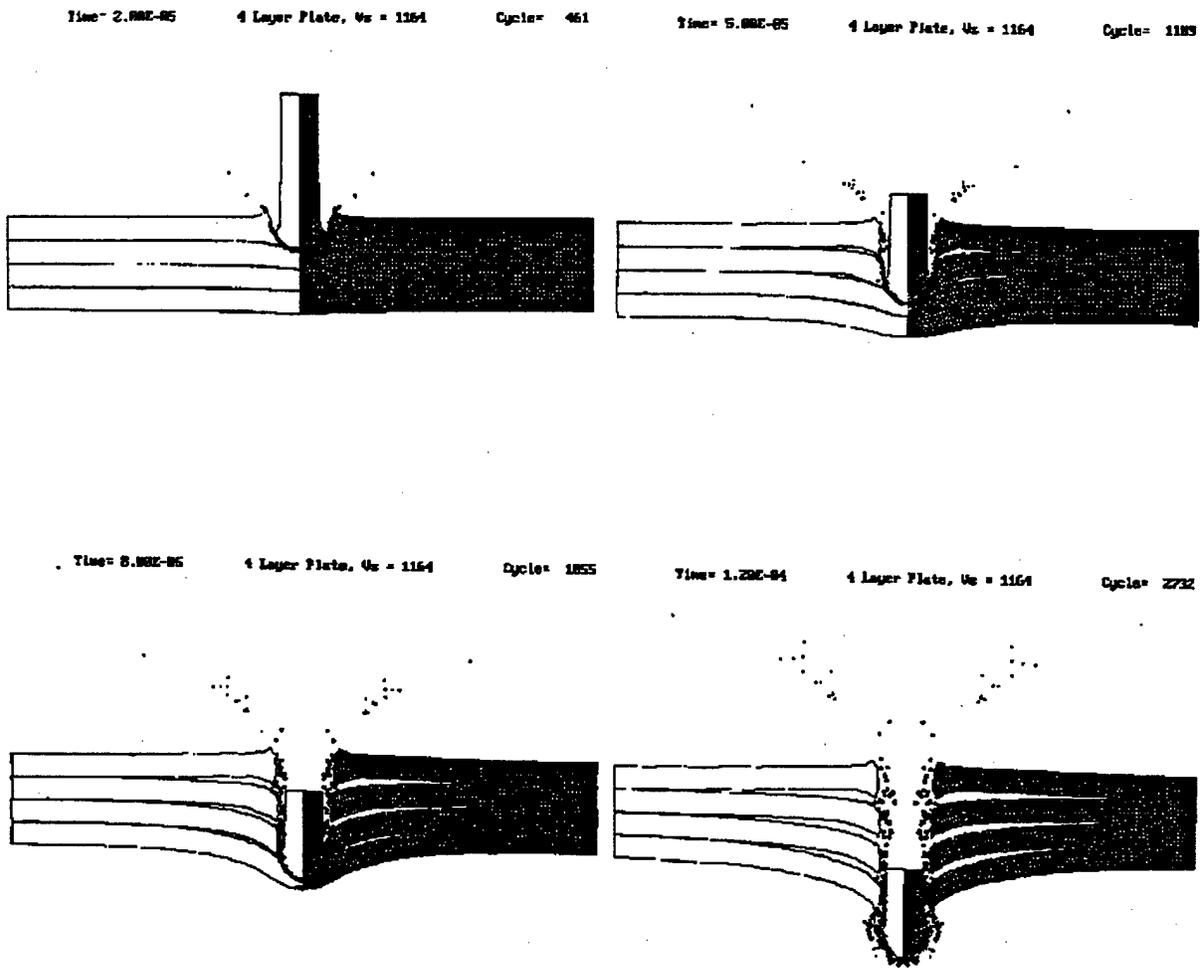


Figure 1. Perforation of a Laminated Plate.

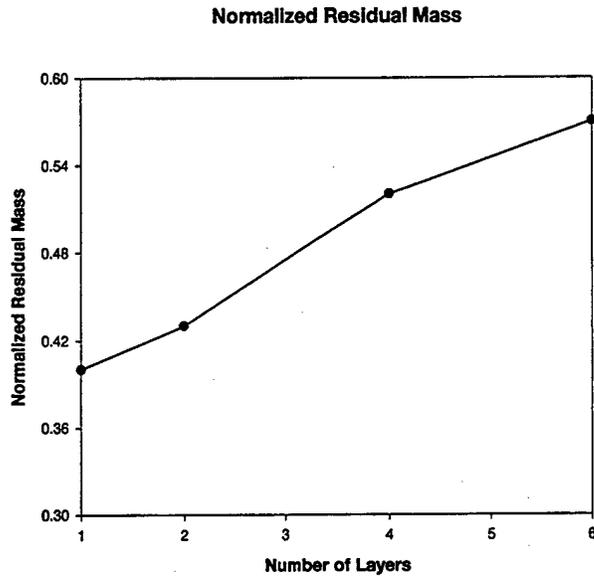


Figure 2. Variation of Projectile Residual Mass With Target Layering.

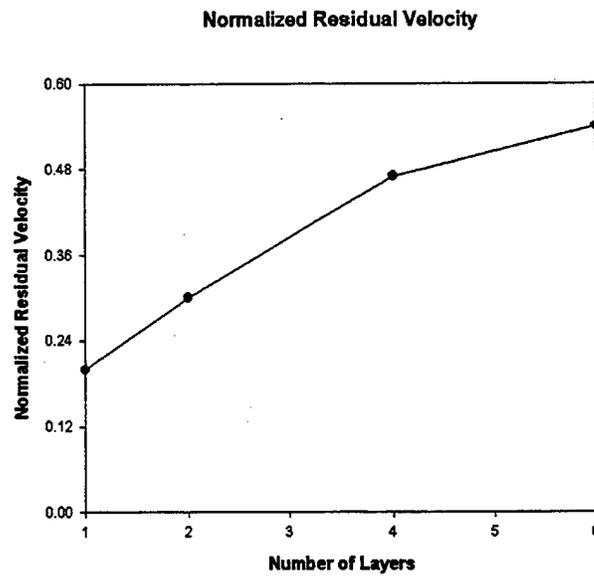


Figure 3. Variation of Projectile Residual Velocity With Target Layering.

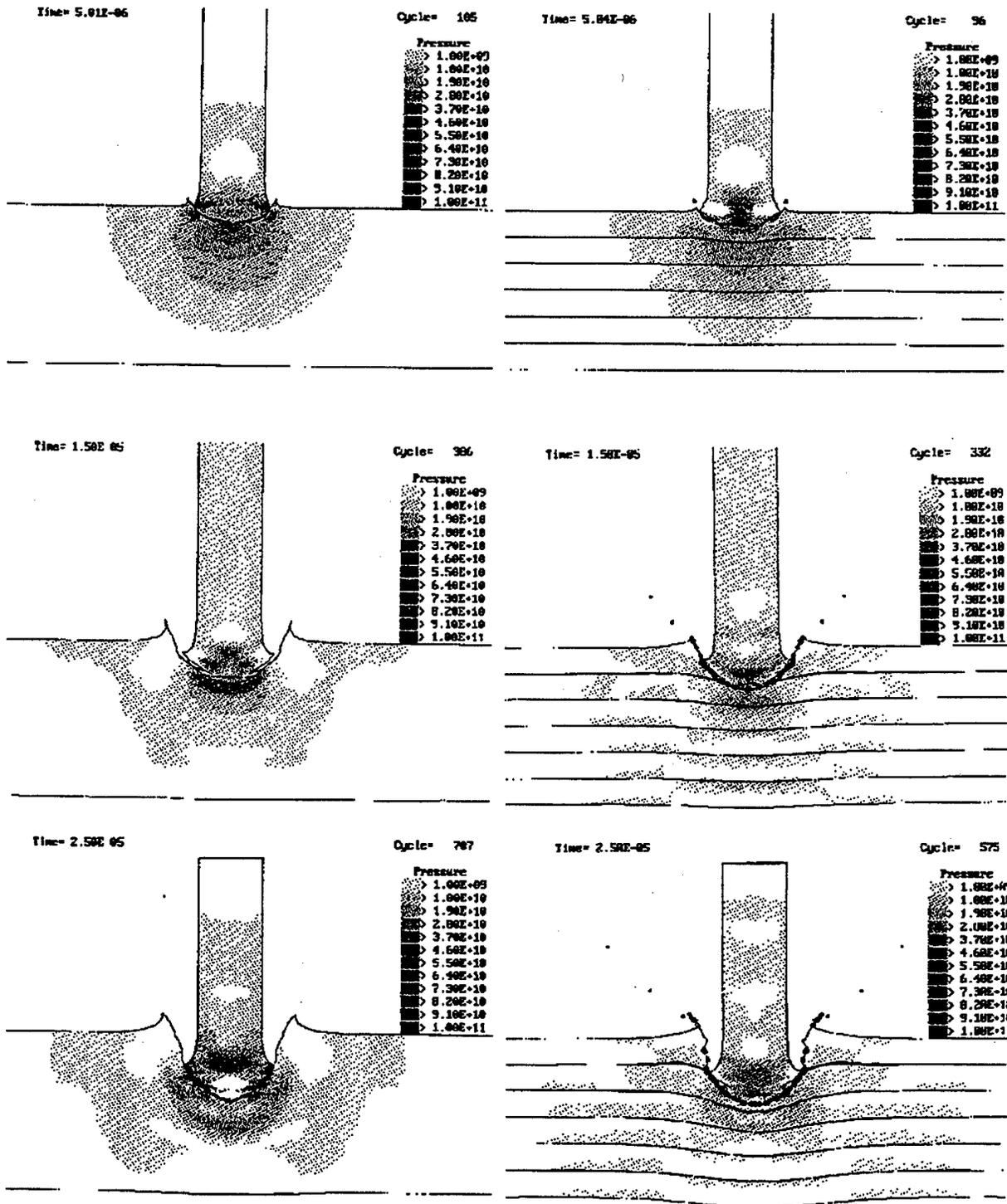


Figure 4. Wave Propagation in Solid and Six Layer Target.

Nixdorff [4], using penetration theories of Awerbuch and Bodner and Lambert and Jonas (both described in Chapter 5 of Zukas et al. [15]), analytically studied the variation in the ballistic limit with the number of plate layers, holding the total plate thickness constant. Nixdorff found that for targets that were subdivided into n layers of equal thickness ". . . the residual velocity has always turned out to be higher, the ballistic limit velocity has always turned out to be lower than for a monolithic target of the same total thickness. This becomes globally more apparent when the number n of subdivisions is raised while keeping the total thickness constant."

2.2 Eulerian Calculations. The January 1998 version of the Eulerian CTH hydrocode [16] was used to model the previously discussed Lagrangian simulations. A series of four simulations was conducted corresponding to a single target plate and two, four, or six plate-layered targets with the same initial conditions as the Lagrangian simulations. All simulations used a mesh consisting of 480×800 cells with a one-to-one aspect ratio throughout. The size of the cells provided 20 cells across the radius of the penetrator. To model sliding between plates, a 0.01 cm gap was introduced between each plate. Additionally, mixed cells were not allowed to support tension.

Figure 5 shows the predicted normalized residual mass as a function of the number of target layers. Because CTH only gives the mass for the individual materials as a global quantity including all material in the mesh, the mass of the residual penetrator had to be estimated. To estimate the residual mass a damage criterion was chosen (damage in the sense of the Johnson-Cook failure model [17] in which material with a damage of 1.0 is assumed fully failed and behaves as a fluid) in which all penetrator material with a damage of 0.99 or greater was assumed to no longer contribute to residual mass. Using this criterion, the Eulerian simulations overpredicted the experimentally determined residual mass for the single-plate target. Additionally, the Eulerian simulations show little sensitivity in predicted residual mass as a function of the number of target layers. The computed residual masses were 39.85 g, 40.57 g, 40.31 g, and 40.52 g for the one, two, four, and eight target-plate layers, respectively.

Residual velocity was predicted to be relatively constant by CTH, at 840 m/s for the monolithic plate and 850 m/s for all layered plate configurations. The lack of sensitivity of the

NORMALIZED RESIDUAL MASS Lagrangian and Eulerian Calculations

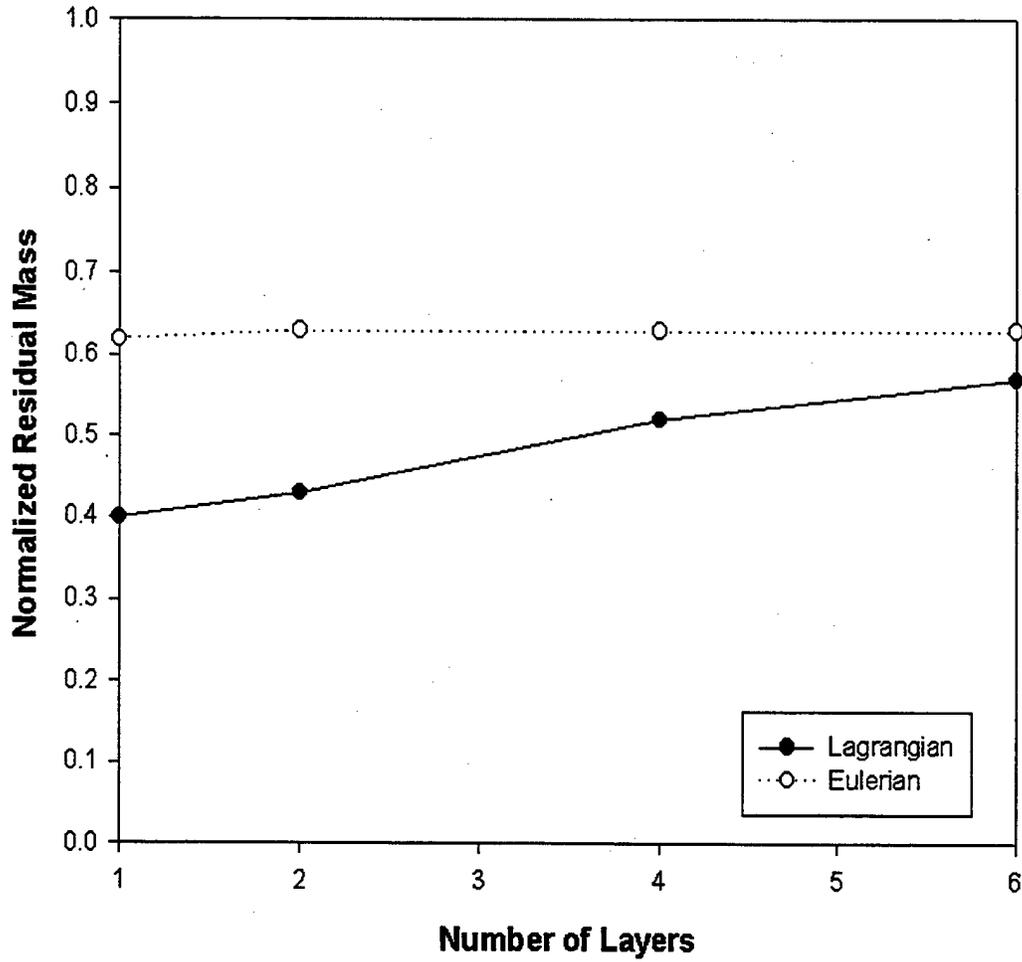


Figure 5. Variation of Projectile Residual Mass With Target Layering Comparing Lagrangian and Eulerian Simulation Results.

results can be explained by the interface treatment used. Eulerian simulations are usually advanced in two distinct phases. In the Lagrangian phase, the mesh is allowed to distort and the simulation is advanced in time. In the advection phase, the distorted mesh is remapped back to the original mesh. The velocities in Eulerian codes are either defined at the cell faces (as in CTH) or at the cell corners (nodes), and all other flow-field variables are cell centered. The implication is that all materials within a mixed cell have the same velocity field, implying a no-slip condition. An attempt to overcome this shortcoming in the CTH code has been made by Walker and Anderson [18]. The authors defined a cell-centered velocity where each material within a mixed cell had its own velocity, which was advected with the material as a state variable. The authors attempted modeling a rigid body perforation with only limited success.

When materials separate, free surfaces are created and stress pulses cannot cross these surfaces. In the Eulerian simulations, the plates were initially separated by 0.1 mm, but this was still less than the width of a single cell; therefore, the free surfaces were in mixed cells. As a result, compressive stress pulses could still pass over the free surfaces even when the individual plates were not in physical contact. For tensile stresses, void is inserted over several computational cycles to relax pressures and allow materials to separate. In the simulations presented here, mixed cells were not allowed to support tension; however, a tensile wave arriving at the interface between target plates will not act as a free surface, as relaxing the stresses by inserting void takes place over several computational cycles.

Today, the simple failure models in hydrocodes are the single biggest limitation of code accuracy. The Lagrangian and Eulerian codes used in this study had different failure models. The effect of these on computational results has not been examined. Failure is modeled only in the grossest sense in both sets of calculations. In the Lagrangian simulations, failure was largely controlled through an ad hoc erosion algorithm in which elements are removed when they reach a user-defined value of equivalent plastic strain (erosion strain). Failure occurs at two levels. At a value of effective plastic strain of 0.40, the elements are no longer able to carry shear or tensile stresses. Only compression is permitted, so the material behaves much as a fluid. At a much higher value, typically between 1.2 - 1.5 in most calculations, the material is assumed to have failed totally.

Failed elements are removed from the calculation, the contact surfaces are redefined for each geometry, and the calculation proceeds. Since mass points associated with failed elements continue to be tracked, this procedure conserved mass and momentum exactly, but total energy only approximately. The Eulerian simulations used the empirical Johnson-Cook damage model with parameters chosen so that material would fail at an equivalent plastic strain of 0.40.

Lagrangian codes provide a straightforward means of defining material interfaces but have problems treating large deformation. On the other hand, Eulerian codes readily treat severe deformation but have certain disadvantages modeling sliding and handling material properties within mixed cells. A potential solution is to use a finer mesh so that several empty cells (void cells) are between the individual plates. Problems, however, would still occur when the initially separated plates come into physical contact.

3. Conclusions

Layering dramatically weakens targets of thin and intermediate thickness. For very thin targets, even the mechanism of penetration may change, while thick targets show small changes in projectile residual properties when compared to their monoblock equivalents.

Lagrangian calculations can do an excellent job of simulating monoblock and multiplate perforation if: (1) care is taken to determine material properties for the constitutive model from wave propagation experiments at appropriate strain rates, and (2) some reasonable estimate of material failure is used. Results of Euler code calculations are very sensitive to the material interface logic used in the code. Despite an appropriate constitutive model and parameters for that model obtained from wave propagation experiments, incorrect results may be obtained in relation to experiments depending on the material transport algorithm chosen.

4. References

1. Rinehart, J. S. "On Fractures Caused by Explosions and Impacts." *Quart Colorado School of Mines*, vol. 55, no. 4, 1960.
2. Tedesco, J. W., and D. W. Landis. "Wave Propagation Through Layered Systems." *Computers & Structures*, vol. 32, nos. 3-4, 1989.
3. Netherwood, P. H. "Rate of Penetration Measurements." ARBRL-MR-02978, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1979.
4. Nixdorff, K. "Some Applications of the Impact Theory of J. Awerbuch and S. R. Bodner." *Trans CSME*, vol. 8, no. 1, pp. 16-20, 1984.
5. Segletes, S. B., and J. A. Zukas. "The Effect of Material Interfaces on Calculations of Plate Penetration." *Recent Advances in Impact Dynamics of Engineering Structures*, edited by D. Hui and N. Jones, AMD-Vol. 105, New York: ASME, 1989.
6. Zukas, J. A. "Effects of Lamination and Spacing on Finite Thickness Plate Perforation." *Structures Under Shock and Impact IV*, edited by N. Jones, C. A. Brebbia, and J. A. Watson, Southampton: Computational Mechanics Publications, pp. 103-115, 1996.
7. Zaid, A. I. O., A. El-Kalai, and F. W. Travis. "An examination of the Perforation of Mild Steel Plate by a Flat-Ended Cylindrical Projectile." *International Journal of Mechanical Sciences*, vol. 15, pp. 129-143, 1973.
8. Eleiche, A. M., M. S. Abdel-Kader, and A. Almohandes. "Penetration Resistance of Laminated Plates from Steel and Fiberglass-Reinforced Polyester." *Structures Under Shock and Impact IV*, edited by N. Jones, C. A. Brebbia, and A. J. Watson, Southampton: Computational Mechanics Publications, pp. 117-126, 1996.
9. Gupta, N. K., and V. Madhu. "An Experimental Study of Normal and Oblique Impact of Hard-Core Projectiles on Single and Layered Plates." *International Journal of Impact Engineering*, vol. 19, nos. 5-6, pp. 395-414, 1997.
10. Littlefield, D. L., C. E. Anderson Jr., Y. Partom, and S. J. Bless. "The Penetration of Steel Targets Finite in Radial Extent." *International Journal of Impact Engineering*, vol. 19, no. 1, pp. 49-62, 1997.
11. Janzon, B., N. Burman, J. Forss, and E. Liden. "EFP Modeling by Numerical Continuum Dynamics on Personal Computers - A Comparison Between PC-DYNA2D, ZeuS, and AUTODYN." *Proceedings of the 13th International Symposium on Ballistics*, Stockholm, Sweden, 1992.

12. Zukas, J. A. "Some Common Problems in the Numerical Modeling of Impact Phenomena." *Computing Systems in Engineering*, vol. 4, no. 1, pp. 43-58, 1993.
13. Lambert, J. P., "The Terminal Ballistics of Certain 65 Gram Long Rod Penetrators Impacting Steel Armor Plate." ARBRL-TR-02027, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1978.
14. Nicholas, T. "Material Behavior at High Strain Rates." AFWAL-TR-80-4053, USAF Wright Aeronautical Laboratories, Wright-Patterson Airforce Base, OH, 1980.
15. Zukas, J.A., T. Nicholas, L. B. Greszczuk, H. F. Swift, and D. R. Curran. *Impact Dynamics*, New York: Wiley, 1982; Republished Malabar, FL: Krieger, 1992.
16. McGlaun, J. M., S. L. Thompson, and M. G. Elrick. "CTH: A Three-Dimensional Shock Wave Physics Code." *International Journal of Impact Engineering*, vol. 10, nos. 1-4, pp. 251-360, 1990.
17. Johnson, G. R., and W. H. Cook. "Fracture Characteristics of Three Metals Subjected to Various Strains, Strain Rates, Temperatures, and Pressures." *Journal of Engineering Fracture Mechanics*, vol. 21, no. 1, pp. 31-48, 1985.
18. Walker, J. D., and C. E. Anderson Jr. "Multi-Material Velocities for Mixed Cells." *High Pressure Science and Technology - 1993*, edited by S. C. Schmidt, J. W. Shaner, G. A. Samara, and M. Ross, Woodbury, NY: American Institute of Physics, pp. 1773-1776, 1993.

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